US012172297B2

(12) United States Patent
Khadivinassab et al.

(10) Patent No.: US 12,172,297 B2
(45) Date of Patent: Dec. 24, 2024

(54) **MECHANICAL HAND, USEFUL IN ROBOTICS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 140 days.

(21) Appl. No.: **18/128,826**

(22) Filed: **Mar. 30, 2023**

(65) **Prior Publication Data**

US 2023/0234242 A1 Jul. 27, 2023

Related U.S. Application Data

(63) Continuation of application No. 17/098,716, filed on Nov. 16, 2020, now Pat. No. 11,639,004.

(60) Provisional application No. 62/937,044, filed on Nov. 18, 2019.

(51) **Int. Cl.**
B25J 15/00 (2006.01)
B25J 13/08 (2006.01)

(52) **U.S. Cl.**
CPC ***B25J 15/0009*** (2013.01); ***B25J 13/084*** (2013.01); ***B25J 13/086*** (2013.01)

(58) **Field of Classification Search**
CPC B25J 15/0009; B25J 13/084; B25J 13/086; B25J 15/08; B25J 15/083; B25J 9/08; B25J 9/144
USPC 294/106, 213
See application file for complete search history.

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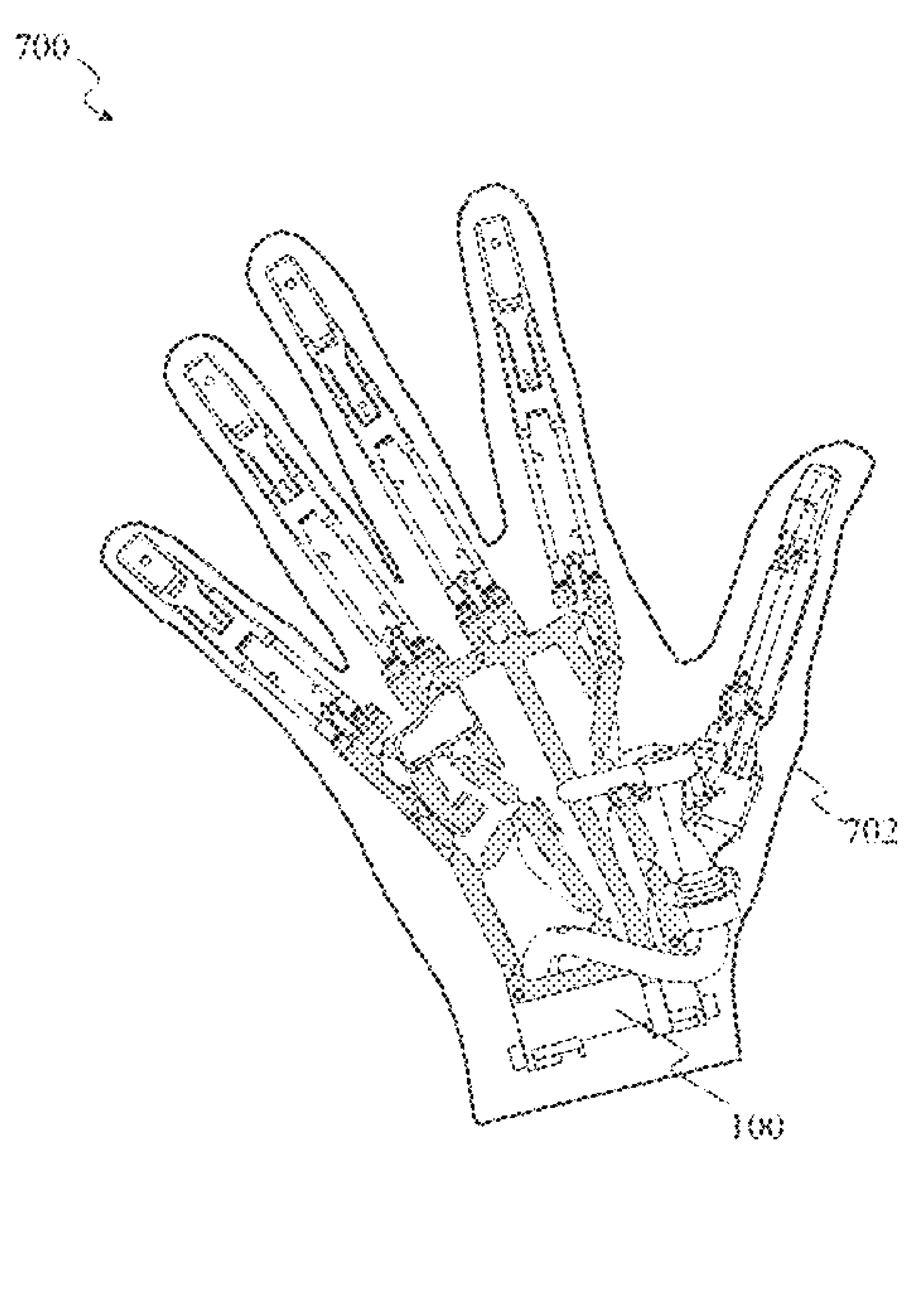
(57) **ABSTRACT**

A mechanical hand mimics a human hand having similar degrees of freedom and sensory abilities while appearing visually similar to human hand. The mechanical hand comprises a mechanical hand skeleton and resilient elastomer (e.g., silicone) skin that fully encloses the mechanical hand skeleton. The mechanical hand skeleton may advantageously be molded directly into the resilient elastomer (e.g., silicone) skin such that the hand appears, moves, and feels very similar to a real human hand. The mechanical hand may have applications in robotics, for example as an end-of-arm tool or end effector, or may have other applications. Robotic applications may include prosthetics applications.

20 Claims, 12 Drawing Sheets



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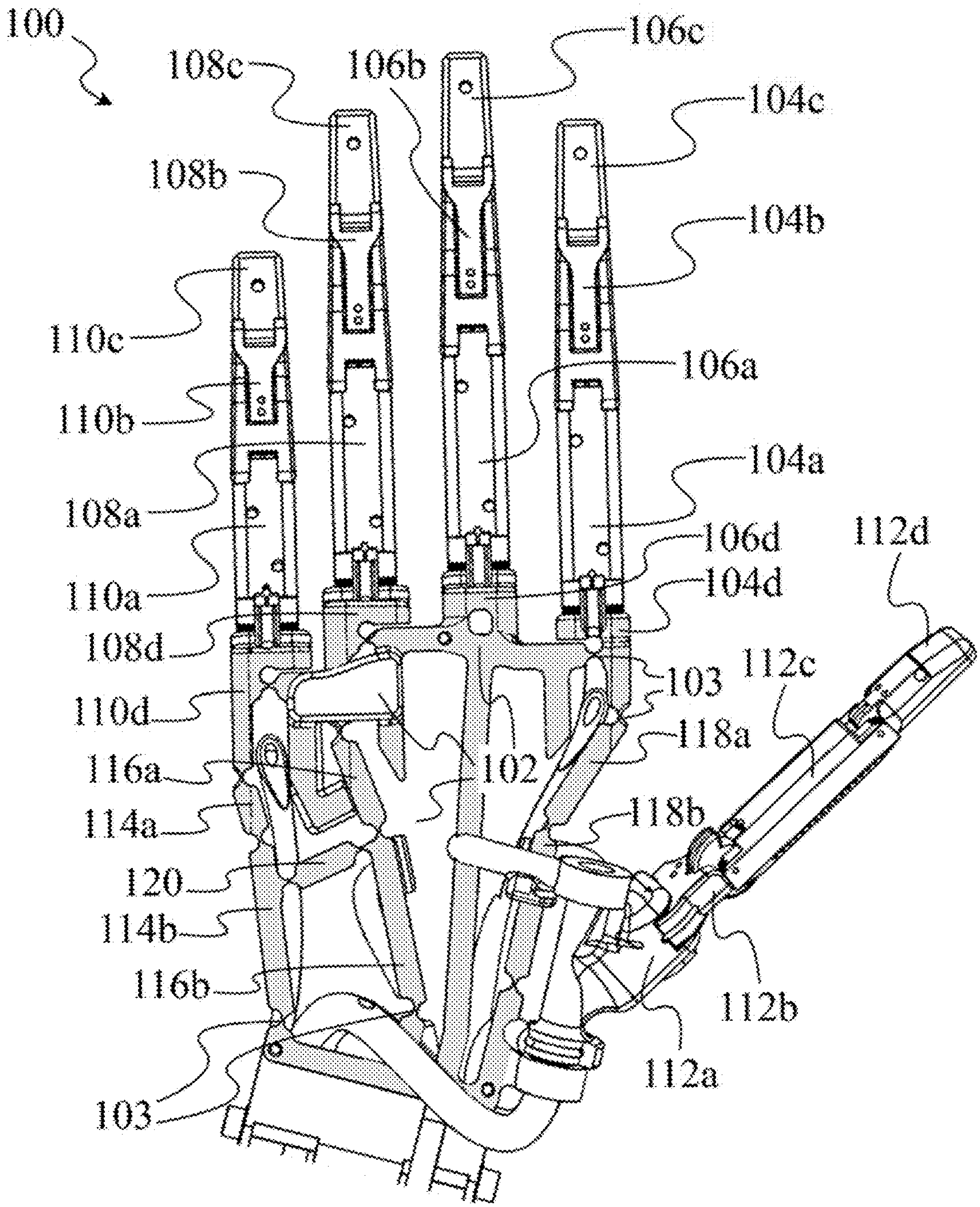
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Fig. 1

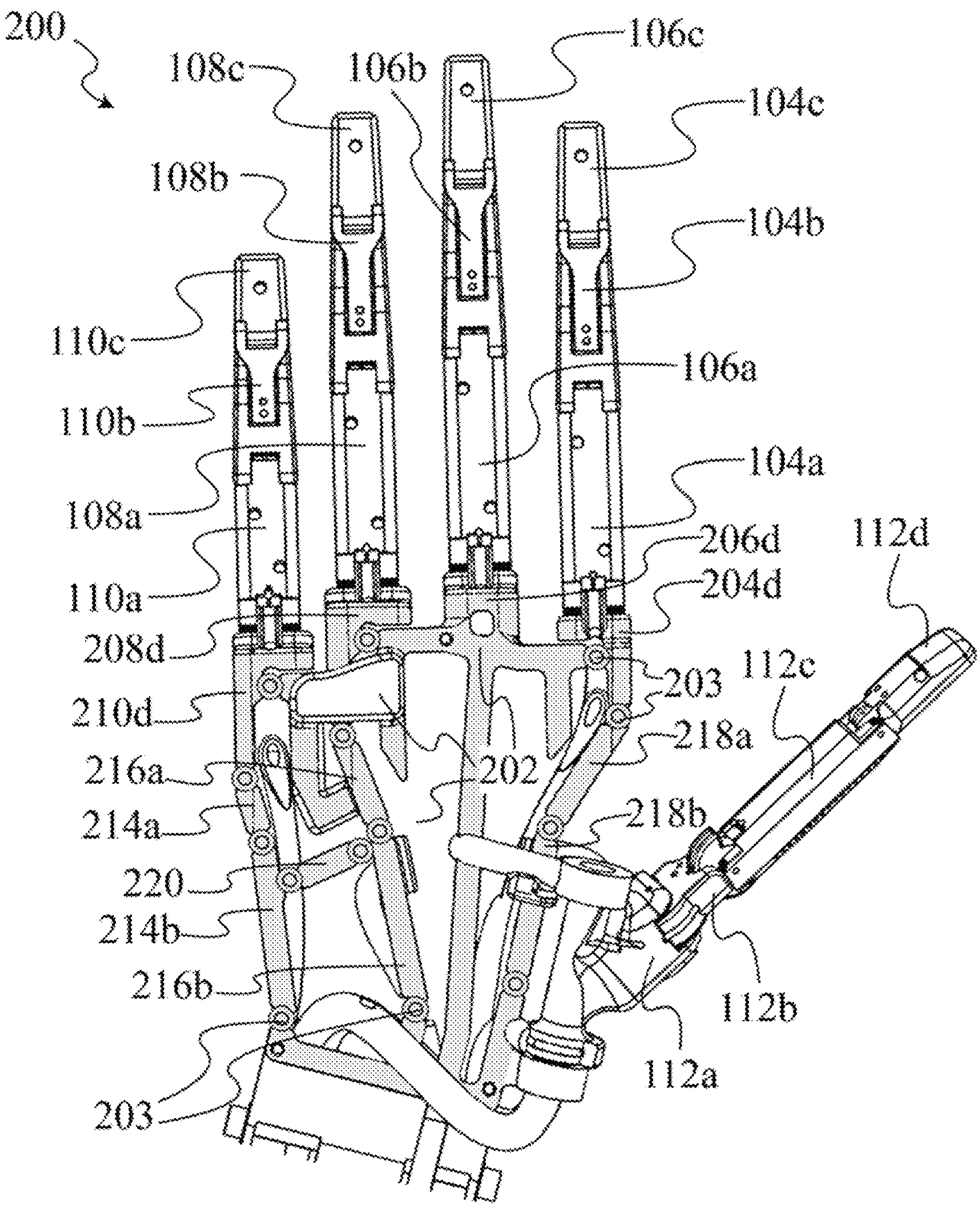
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Fig. 2

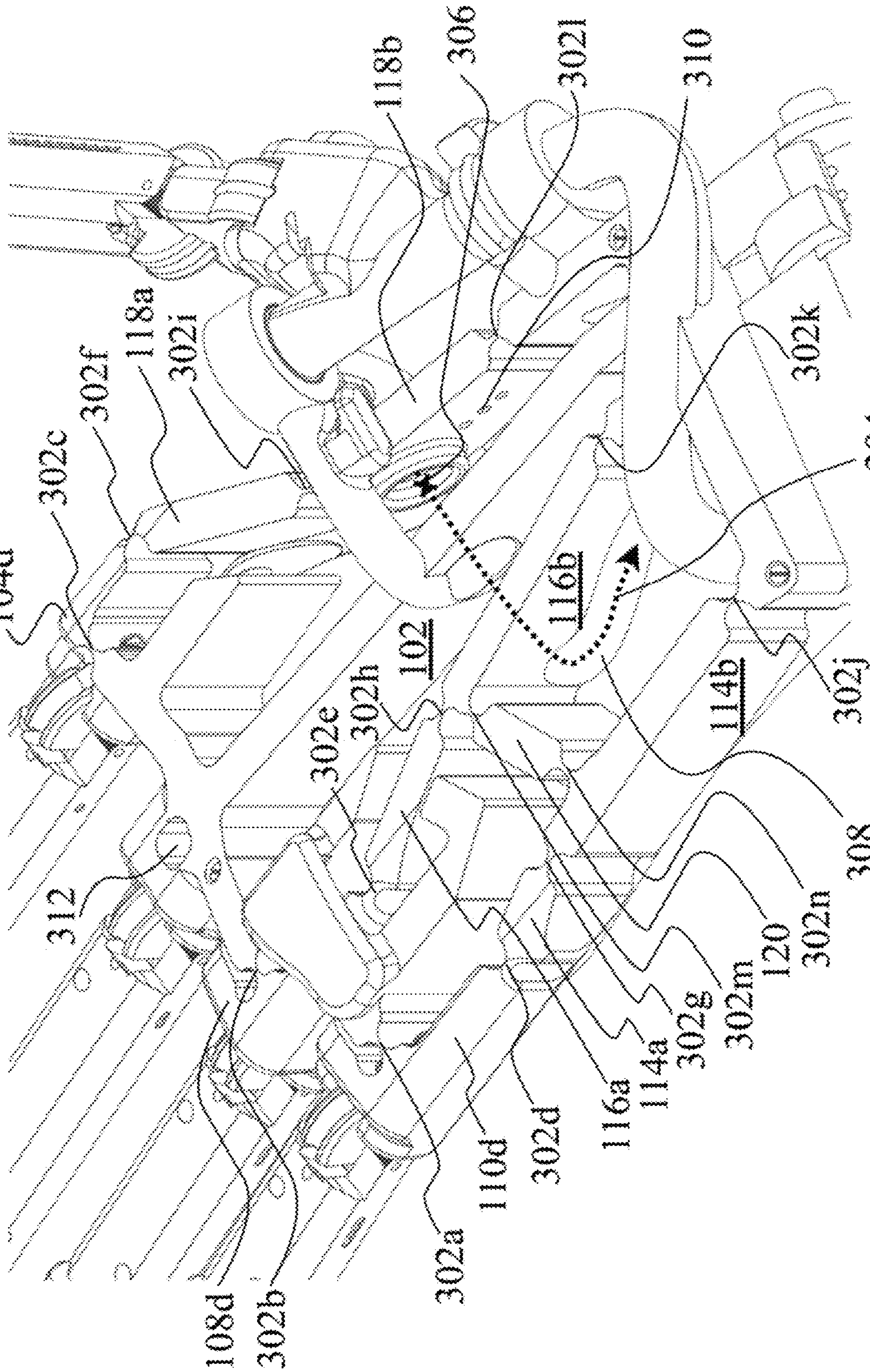
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Fig. 3

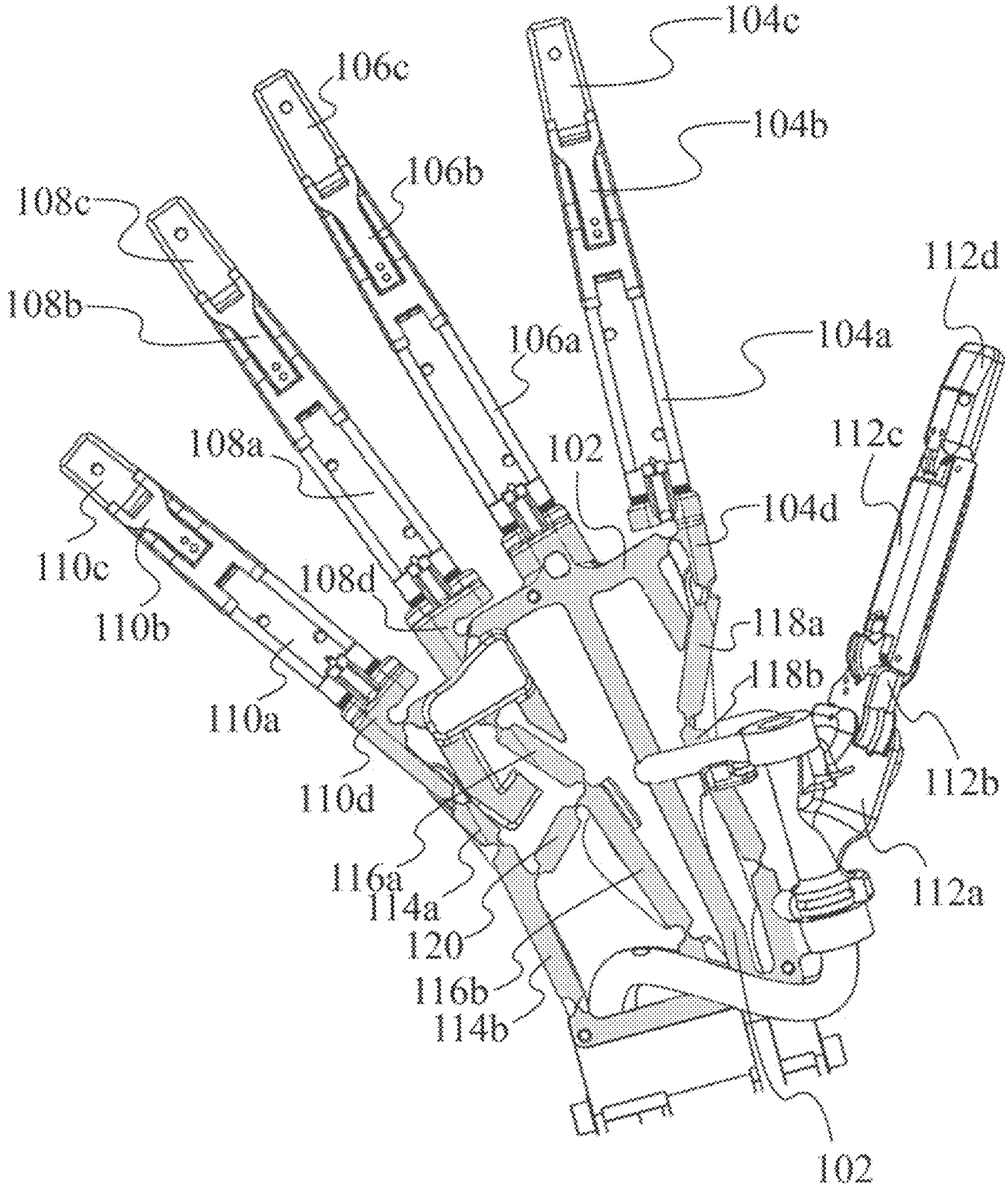
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Fig. 4

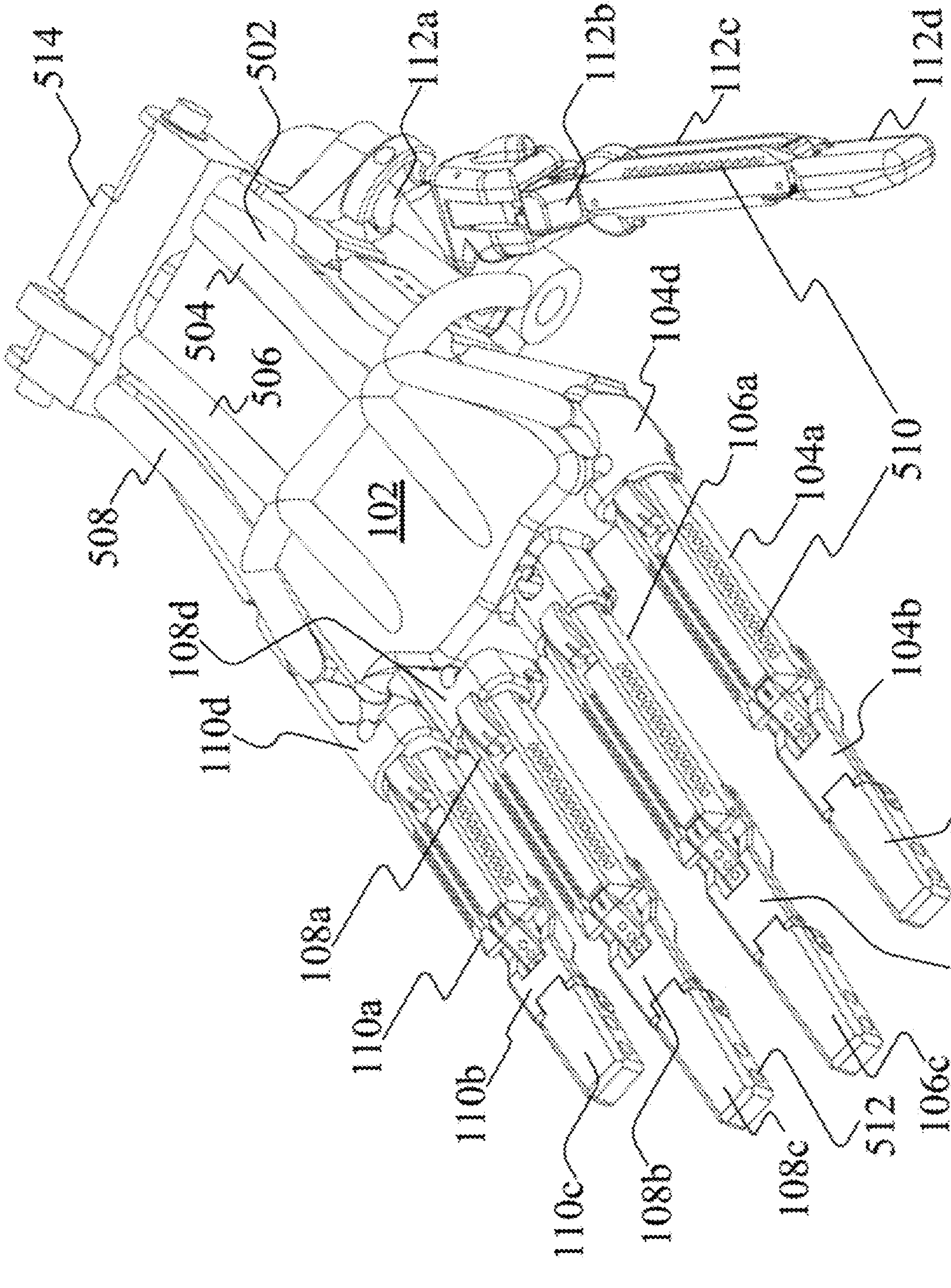
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Fig. 5

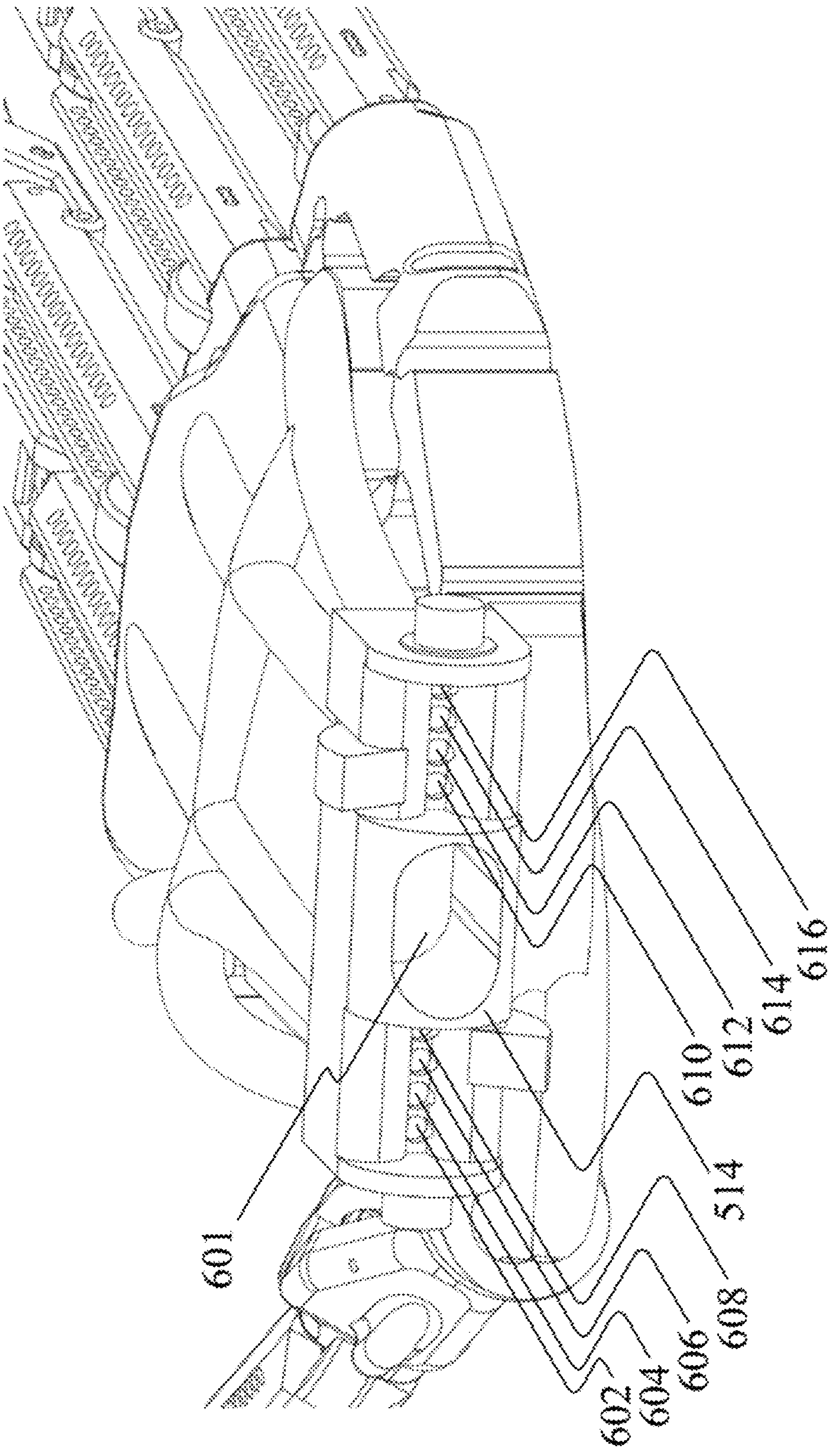

Fig. 6

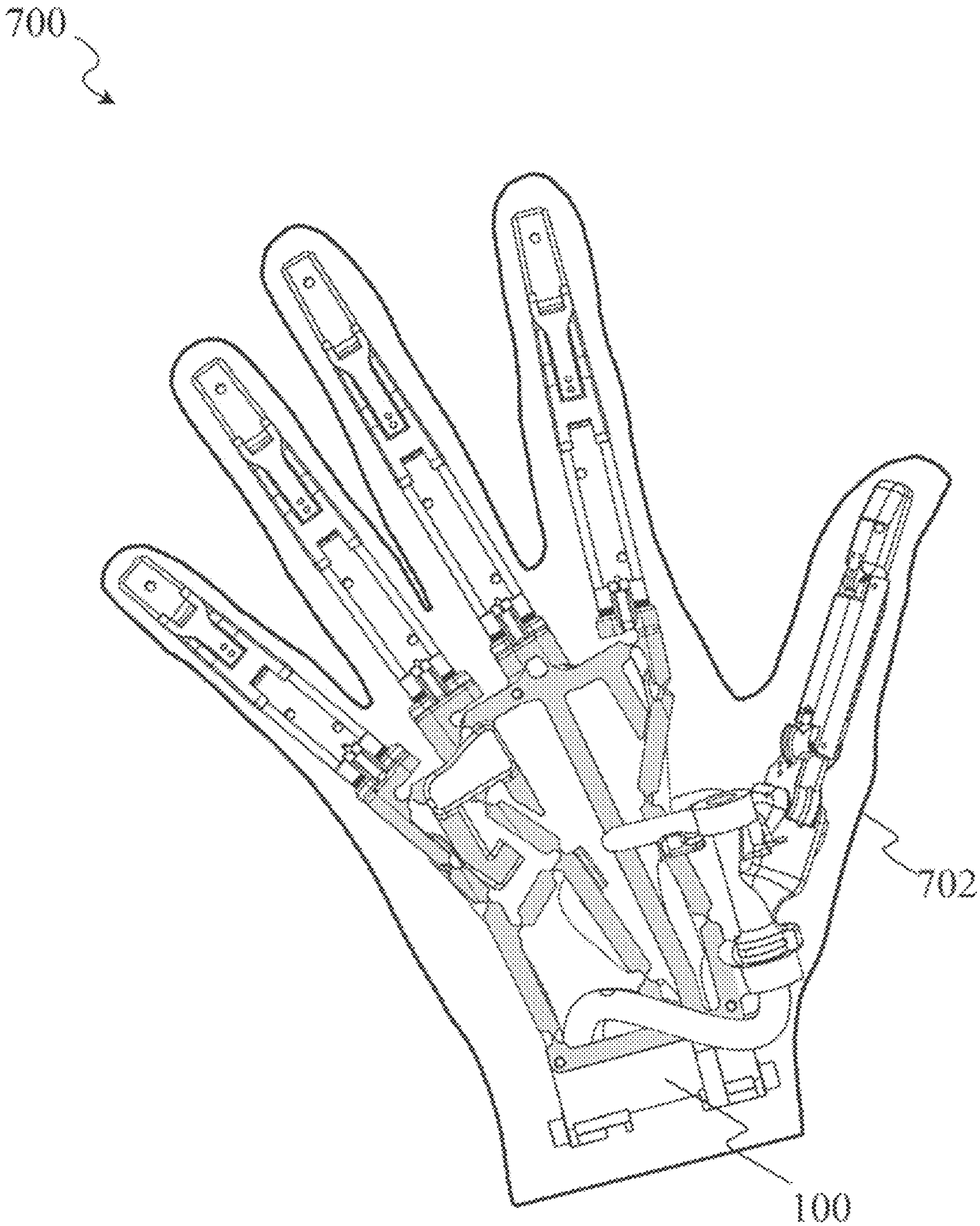

Fig. 7

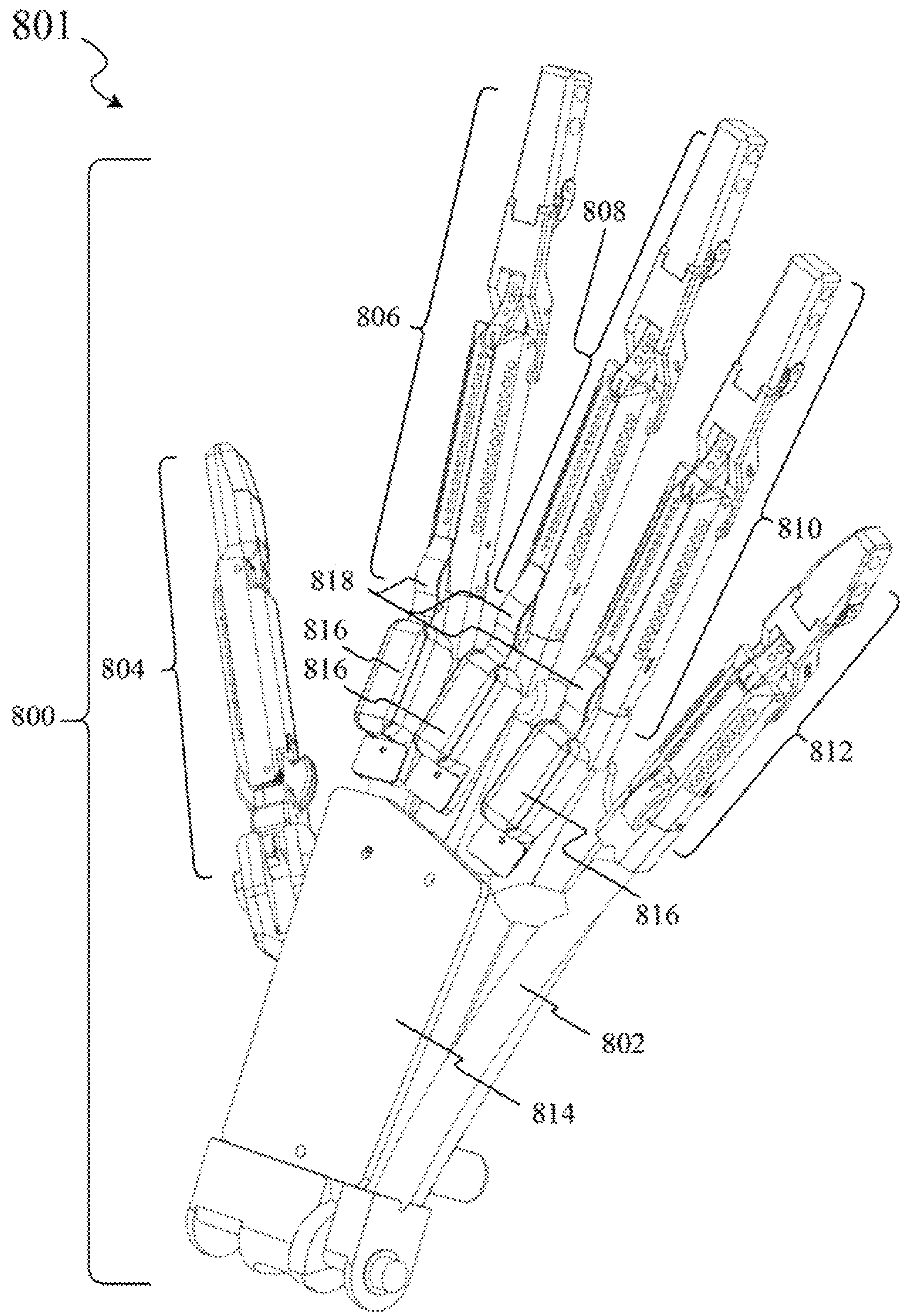

Fig. 8

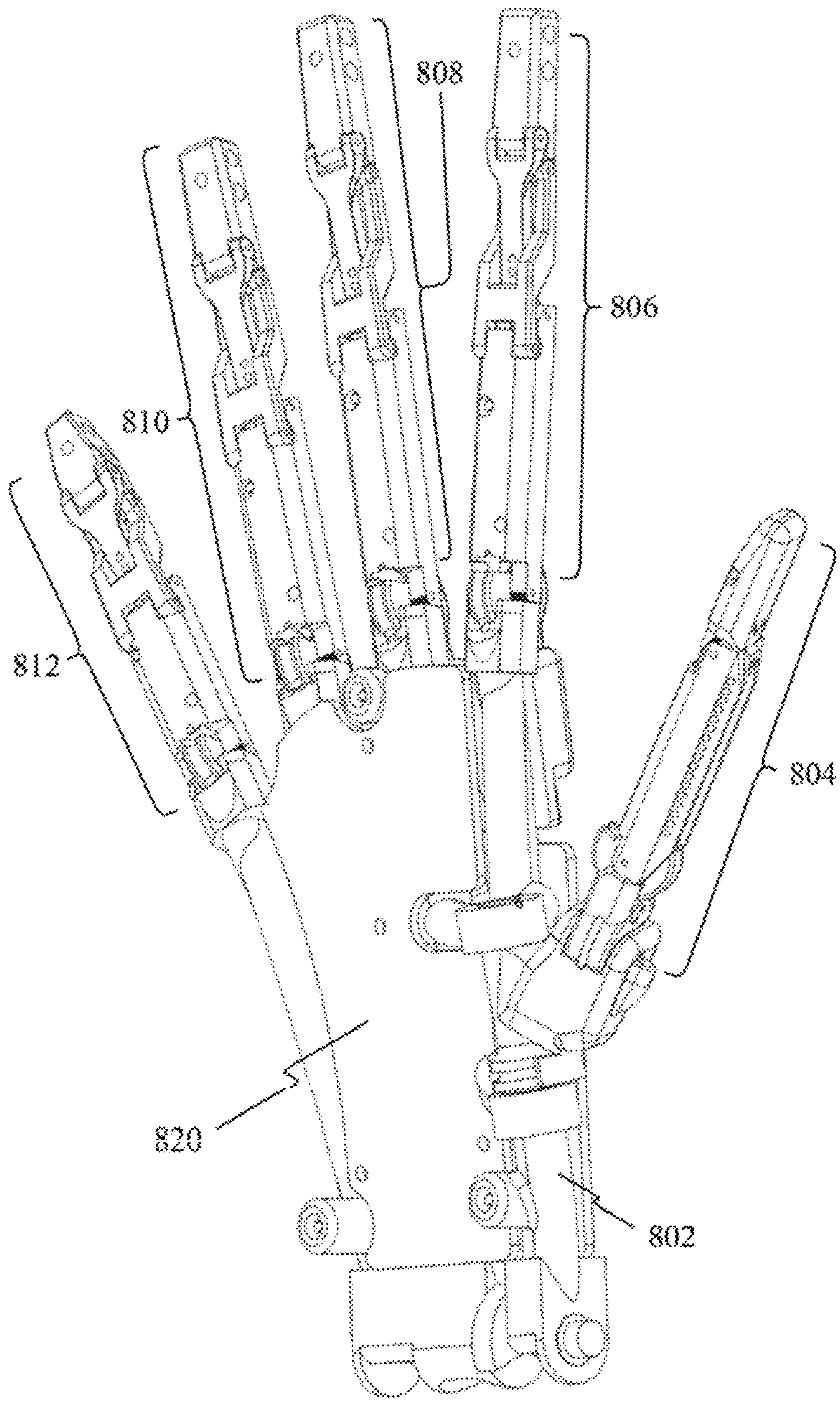

Fig. 9

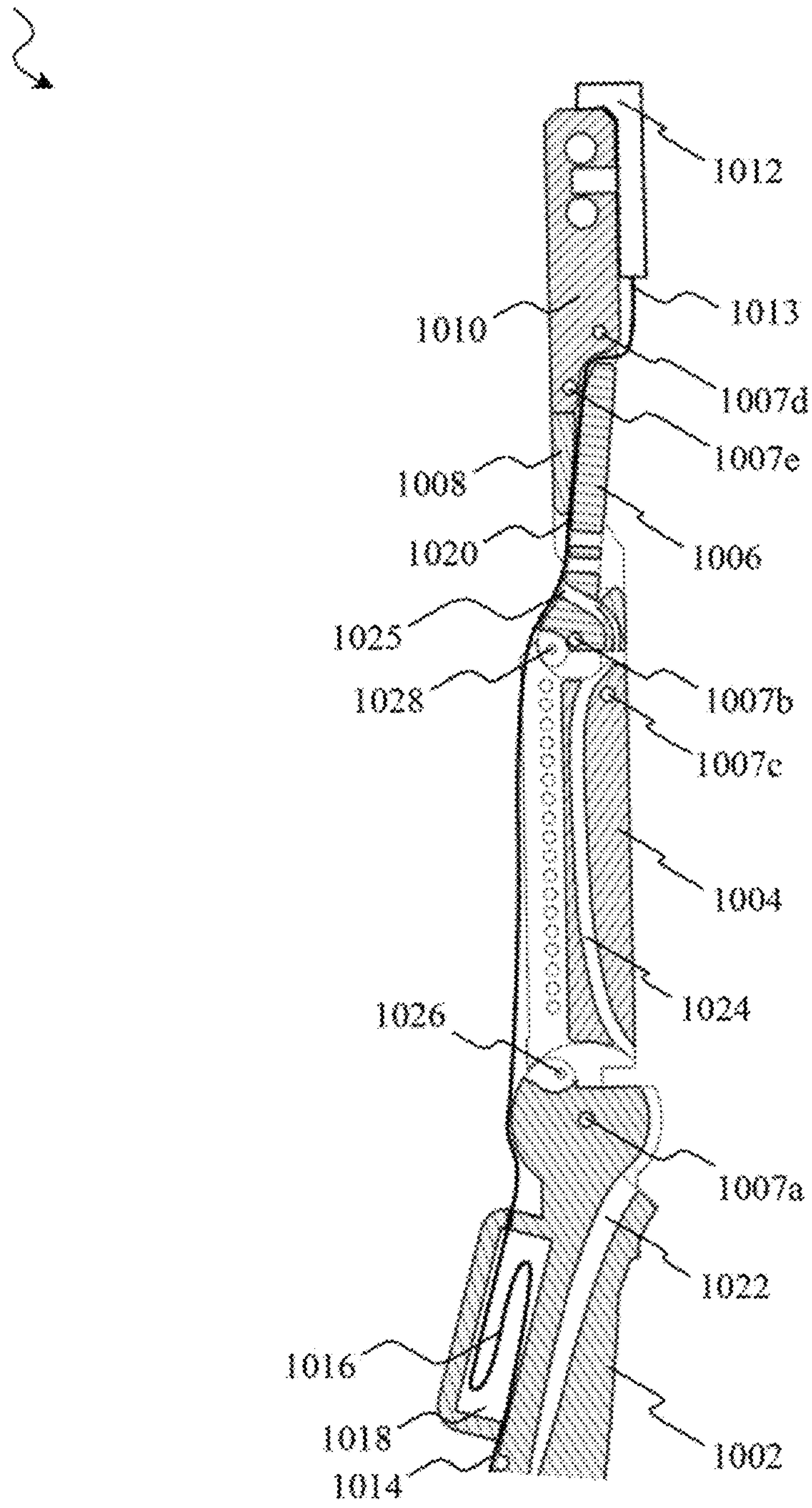
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Fig. 10

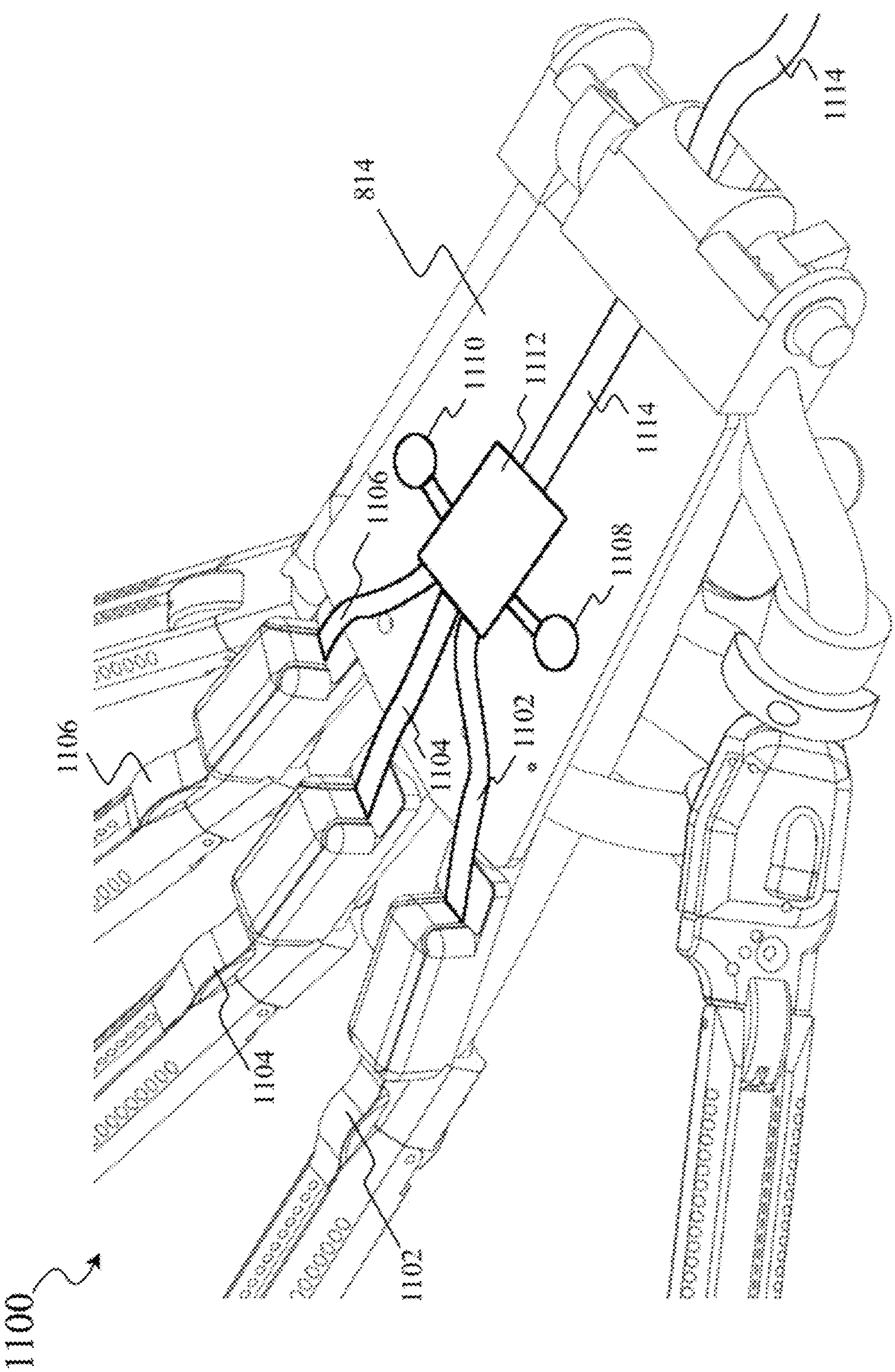
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Fig. 11

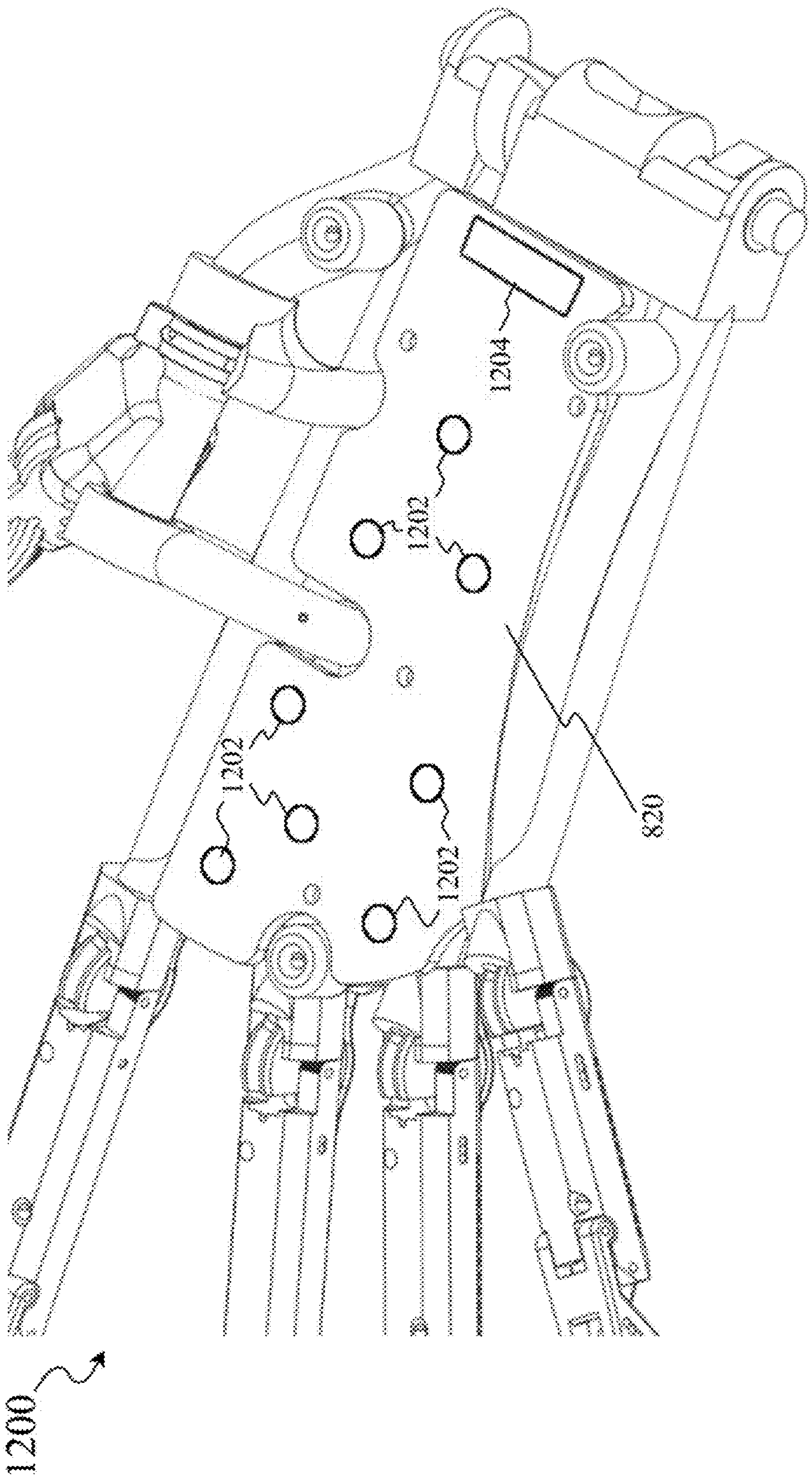

Fig. 12

MECHANICAL HAND, USEFUL IN ROBOTICS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 17/098,716, filed on Nov. 16, 2020, which claims benefit of U.S. Provisional Application No. 62/937,044, filed on Nov. 18, 2019, the contents of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

The present disclosure generally relates to mechanical hands, for example mechanical hands useful for use in robotics.

BACKGROUND

Description of the Related Art

Robots or robotic appendages typically employ an end-of-arm tool or end effector to interact with objects in an environment in which the robot operates. Some end-of-arm tools or end effectors are relatively simple articles, without moving elements (e.g., push bar, hook, suction cup) allowing simple interactions or engagement (e.g., push, pull, lift) with objects in the environment. Other end-of-arm tools or end effectors are relatively complex machines, with moving elements (e.g., grippers, digits) allowing complex interactions or engagement (e.g., grasping) with objects in the environment.

As the field of robots develops, more sophisticated and/or robust end-of-arm tools or end effectors are desirable.

BRIEF SUMMARY

A mechanical hand mimics a human hand having similar degrees of freedom and sensory abilities while appearing visually similar to human hand. The mechanical hand comprises a mechanical hand skeleton and resilient elastomer (e.g., silicone) skin that fully encloses the mechanical hand skeleton. The mechanical hand skeleton may advantageously be molded directly into the resilient elastomer (e.g., silicone) skin such that the hand appears, moves, and feels very similar to a real human hand. The mechanical hand may have applications in robotics, for example as an end-of-arm tool or end effector, or may have other applications. Robotic applications may include prosthetics applications.

A mechanical hand may be summarized as comprising: a palm; at least three mechanical digits, each of the mechanical digits respectively comprised of at least three mechanical links, at least two curl joints, and having a tip and a base, the base of each of the mechanical digits coupled to the palm, the mechanical links of each pair of successive mechanical links along each of the mechanical digits between the tip and the base pivotally coupled to one another via a respective one of the at least two curl joints; a plurality of mechanical tendons, each of the mechanical tendons coupled to at least one of the mechanical links of the mechanical digits; and a skin of an elastic material that completely envelopes at least the palm and the mechanical digits.

The mechanical hand may further comprise: at least one sensor, the at least one sensor positioned at least proximate the tip of at least one of the mechanical digits, wherein the skin also completely envelopes the at least one sensor. The

at least one sensor may be at least one of a pressure sensor or a proximity sensor. The mechanical hand may further comprise: at least one wire, the at least one wire electrically coupled to the at least one sensor, wherein the skin also completely envelopes the at least one wire. The at least one of wire may include an electrically insulative sleeve and extends at least to the palm.

The palm may have a proximate portion and a distal portion, the mechanical digits coupled at least proximate the distal portion of the palm, and further comprises: a mechanical wrist connection interface, the mechanical wrist connection interface coupled to or part of the distal portion of the palm.

The skin may also completely envelope the mechanical wrist connection interface.

The mechanical hand may further comprise: a plurality of tubes; and wherein each of the mechanical tendons are respectively comprised by at least one cable and the at least one cable is coupled to at least one of the mechanical links of the mechanical digits, each of the cables passing through at least one of the tubes, and wherein the skin also completely envelopes the tubes.

The mechanical hand may further comprise: a mechanical wrist connection interface, the mechanical wrist connection interface coupled to or part of a distal portion of the palm.

The palm may have a plane defined by a major face of the palm, and the curl joints of each of the mechanical digits that pivotally couple the links of each of the pair of links to one another each pivot about a respective axis that allow the tip of the respective mechanical digit to curl toward and away from the plane of the palm, For each of at least two of the mechanical digits, a respective plurality of sweep joints that pivotally couple the base of the respective mechanical digit to the palm to pivot the respective mechanical digit towards or away from one another, wherein the skin also completely envelopes the plurality of sweep joints, for example pivot about respective axes that are substantially (i.e., within 30 degrees) perpendicular to the plane of the palm.

Each sweep joint may be a respective flexure joint.

The mechanical hand may further comprise: for at least two of the at least three of the mechanical digits, at least one inter-digit joint that movably directly couples pairs of the mechanical digits to one another. Each inter-digit joint may be a respective flexure joint.

The mechanical hand may further comprise: for at least three of the mechanical digits, a respective plurality of sweep joints that pivotally couple the base of the respective mechanical digit to the palm to pivot the respective mechanical digit towards or away from one another, wherein the skin also completely envelopes the plurality of sweep joints.

The mechanical hand may further comprise: at least one of the palm or the mechanical digits comprise a plurality of through-holes and the skin extends through the through-holes to mechanically couple the skin to the at least one of the palm or the mechanical digits.

The skin may be a silicone skin molded directly about and through the palm and mechanical digits.

The curl joints of each of the mechanical digits that pivotally couple the links of each of the pair of links to one another may be a respective flexure joint. The curl joints of each of the mechanical digits that pivotally couple the links of each of the pair of links to one another may be a respective hinge joint with a respective pin.

At least three mechanical digits may comprises four mechanical fingers and a mechanical thumb coupled to the palm to move in opposition to the mechanical fingers.

The base of each of the mechanical digits may be coupled to the palm via a respective one of the curl joints of the mechanical digit and each curl joint that pivotally couples the base of the respective mechanical digit to the palm is a flexure joint. The base of each of the mechanical digits may be coupled to the palm via a respective one of the curl joints of the mechanical digit and each curl joint that pivotally couples the base of the respective mechanical digit to the palm is a hinge joint with a respective pin.

A method of manufacturing a mechanical hand comprises coupling at least three mechanical digits to a palm, each of the mechanical digits respectively comprised of at least two curl links, at least one joint, and having a tip and a base, the base of each of the mechanical digits coupled to the palm, the mechanical links of each pair of successive mechanical links along each of the mechanical digits between the tip and the base pivotally coupled to one another via a respective curl joint; coupling each of a plurality of tendons to at least one of the mechanical links of respective ones of the mechanical digits; and molding a skin of an elastic material with at least the palm and the mechanical digits in a mold to completely envelope at least the palm and the mechanical digits.

The method may further comprise: positioning at least one sensor at least proximate the tip of at least one of the mechanical digits, electrically coupling at least one wire electrically to the at least one sensor, and wherein the skin also completely envelopes the at least one sensor, and wherein molding a skin of an elastic material to completely envelope at least the palm and the mechanical digits includes molding a skin of silicone with at least the palm, the mechanical digits, and the at least one wire in the mold to completely envelope at least the palm, the mechanical digits, the at least one sensor and the at least one wire.

Each of the tendons may be respectively comprised by at least one cable, and the method may further comprise: providing a plurality of tubes; and passing each of the cables through at least one of the tubes, and wherein molding a skin of an elastic material to completely envelope at least the palm and the mechanical digits includes molding a skin of silicone with at least the palm, the mechanical digits, and the tubes in the mold to completely envelope at least the palm, the mechanical digits, and the tubes.

The method may further comprise: providing a mechanical wrist connection interface on the palm to which a mechanical wrist is coupleable to provide at least one degree of freedom of the palm with respect to the mechanical wrist, wherein molding a skin of an elastic material to completely envelope at least the palm and the mechanical digits includes molding a skin of silicone with at least the palm, the mechanical digits, and the mechanical wrist in the mold to completely envelope at least the palm, the mechanical digits, and the mechanical wrist.

The method may further comprise: providing a plurality of through-holes in at least one of the palm or mechanical digits such that the skin through into the through-holes to mechanically couple the skin to the at least one of the palm or the mechanical digits.

A mechanical hand may be summarized as comprising: a palm, having a finger side, a wrist side, a thumb side, a front face, and a back face, five mechanical digits, each of the mechanical digits respectively having at least two links and at least one joint, each mechanical digit having a tip on one end of the respective mechanical digit and a base another end of the respective mechanical digit, each mechanical digit coupled to the palm at the base of the mechanical digit, wherein four of the mechanical digits are mechanical fingers, the base of each of the mechanical fingers is coupled to the palm on the finger side, one of the mechanical digits is a mechanical thumb, the base of the mechanical thumb is coupled to the thumb side of the palm, and, wherein at least one set of the mechanical digits comprising at least one mechanical digit can be actuated in at least one degree of freedom, the at least one degree of freedom being a pitch of at least one joint of the at least one mechanical digit in each of the at least one set of mechanical digits; a plurality of spreading joints coupled to the palm allow the four mechanical fingers to spread apart from one another, such that each of at least three of the four mechanical fingers rotates around an axis normal to the back face of the palm; and an enveloping layer of an elastic material covering the digits, the palm, and the spreading joints, wherein the digits, the palm, and the spreading joints are embedded in the material.

The spreading joints may comprise: four finger attachment links to which the base of each mechanical finger is coupled to, at least three of the finger attachment links are rotatable finger attachment links coupled to the palm such that the finger attachment links can rotate around an axis normal to the face of the palm, at least three lever arms coupled to or part of the at least three rotatable finger attachment links extending from the at least three rotatable finger attachment links in a direction parallel to the front face of the palm, wherein each of the at least three lever arms is coupled to the palm through at least a primary lever link and a secondary lever link, and at least one lever link connector, the lever link connector coupled at a first end thereof to a secondary lever link of a first lever arm and at a second end thereof to a secondary lever link of a second lever arm, the first and the second lever arms being adjacent lever arms.

The mechanical hand may further comprise: a cable connection point coupled to or part of a first secondary lever link, a cable routing point coupled to or part of a second secondary lever link, a cable routed through the cable routing point and coupled to the cable connection point such that tension can be applied between the cable routing point and the cable connection point by tensioning the cable to control an amount of spreading between at least two of the mechanical fingers. The rotation of the mechanical fingers is such that at least one finger on a first end of the finger side of the palm rotates in the opposite direction to the direction that at least one finger on a second end on the finger side of the palm rotates.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example, the shapes of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

FIG. **1** is a back plan view of a mechanical hand skeleton according to at least one illustrated implementation, the mechanical hand skeleton including a palm and a plurality of mechanical digits and flexure joints, the mechanical digits including an index finger base rotatably coupled to the palm via a flexure joint to rotate around an axis approximately perpendicular to the palm, the mechanical hand skeleton illustrated in a relatively neutral or unspread or relaxed configuration in which at least some of the mechanical digits are not spread with respect to one another.

FIG. **2** is a back plan view of a mechanical hand skeleton according to at least one illustrated implementation, the mechanical hand skeleton including a palm and a plurality of mechanical digits and pin joints, the mechanical digits including an index finger base rotatably coupled to the palm via a pin joint to rotate around an axis approximately perpendicular to the palm, the mechanical hand skeleton illustrated in a relatively neutral or unspread or relaxed configuration in which at least some of the mechanical digits are not spread with respect to one another.

FIG. **3** is a back, left, bottom isometric view of a portion of the mechanical hand skeleton of FIG. **1**, better illustrating various aspects thereof.

FIG. **4** is a back plan view of a mechanical hand skeleton of FIG. **1** illustrated in a relatively spread or tensioned configuration in which at least some of the mechanical digits are spread with respect to one another.

FIG. **5** is a front, right, top, isometric view of a mechanical hand skeleton of FIG. **1** illustrated in a relatively unspread or relaxed configuration.

FIG. **6** is a bottom, front, left, isometric view of a mechanical hand skeleton of FIG. **1** or **2**, better illustrating a wrist connection interface of the mechanical hand skeleton, according to at least one illustrated implementation.

FIG. **7** is a back plan view of a mechanical hand according to at least one illustrated implementation, the mechanical hand comprising mechanical hand skeleton cast in an elastomeric material (e.g., silicone) according to at least one illustrated implementation, the elastomeric material illustrated as transparent to better illustrated the placement of the mechanical hand skeleton therein.

FIG. **8** is a front, right isometric view of a mechanical hand skeleton according to at least one illustrated implementation, the mechanical hand skeleton including a palm and a plurality of mechanical digits and flexure joints, the mechanical digits including an index finger base rotatably coupled to the palm via a flexure joint to rotate around an axis approximately perpendicular to the palm, the mechanical hand skeleton illustrated in a relatively spread or tensioned configuration in which at least some of the mechanical digits are spread apart with respect to one another.

FIG. **9** is a back, left isometric view of the mechanical hand skeleton of FIG. **8**, better illustrating various portions thereof.

FIG. **10** is a cross-sectional view of a finger digit of a mechanical hand skeleton according to at least one illustrated implementation, the cross section taken along a plane that passes through a longitudinal axis of the finger digit.

FIG. **11** is a front, left, bottom isometric view of a portion of a mechanical hand skeleton according to at least one illustrated implementation, illustrating a plurality of finger sensor modules, a first printed circuit board, and ribbon cables providing communicative coupling between first printed circuit board and the finger sensor modules.

FIG. **12** is a back, right, bottom isometric view of a portion of a mechanical hand skeleton according to at least one illustrated implementation, illustrating a plurality of finger sensor modules, a second printed circuit board that bears a number of pressure or touch sensor modules and a controller or processor communicatively coupled to the pressure or touch sensor modules.

DETAILED DESCRIPTION

In the following description, certain specific details are set forth in order to provide a thorough understanding of various disclosed implementations and embodiments. However, one skilled in the relevant art will recognize that implementations and embodiments may be practiced without one or more of these specific details, or with other methods, components, materials, etc. In other instances, certain structures associated with robots, robotic appendages, linkages, and cables or actuators, have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the implementations or embodiments.

Unless the context requires otherwise, throughout the specification and claims which follow, the word "comprise" and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is, as "including, but not limited to."

Reference throughout this specification to "one implementation" or "an implementation" or to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the implementation or embodiment is included in at least one implementation or embodiment. Thus, the appearances of the phrases "one implementation" or "an implementation" or "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same implementation or embodiment. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more implementations or embodiments.

The terms "apparatus" and "mechanism" are used interchangeably herein.

As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the content clearly dictates otherwise. It should also be noted that the term "or" is generally employed in its sense including "and/or" unless the content clearly dictates otherwise.

The headings and Abstract of the Disclosure provided herein are for convenience only and do not interpret the scope or meaning of the embodiments.

Described herein is an example implementation of a mechanism or apparatus and methods for the manufacture of such mechanism or apparatus that approximates the functional and structural characteristics of a human hand. Those skilled in the art would recognize that many features of the implementation can be grouped together, split apart, reorganized, removed, or duplicated. While useful in robotics, for instance as a robotic appendage, the mechanism can be used in a large variety of other practical applications such as, for example, a prosthetic hand.

FIG. **1** illustrates a mechanical hand skeleton **100**, according to at least one illustrated implementation.

The mechanical hand skeleton **100** comprises a palm **102** and a number of mechanical digits (e.g., mechanical fingers, mechanical thumb) moveably coupled to the palm **102**.

An index finger base **104*d*** is rotatably coupled to palm **102** through a flexure joint **103** (only a subset of the flexure joints are indicated on the figure to avoid unnecessary cluttering). The flexure joint **103** allows the index finger base **104*d*** to rotate around an axis that is approximately perpendicular to a face of the palm **102**. A first index finger link **104*a*** is rotatably coupled to the index finger base **104*d***, a second index finger link **104*b*** is rotatably coupled to the first index finger link **104*a***, and a third index finger link **104*c*** is rotatably coupled to the second index finger link **104*b***, such that index finger links **104*a***, **104*b***, and **104*c***, form an index finger able to curl similarly to a human index finger. A first middle finger link **106*a*** is rotatably coupled to a middle finger base **106*d***, which may be coupled to or part of the palm **102**, a second middle finger link **106***b* is rotatably coupled to the first middle finger link **106***a*, and a third middle finger link **106***c* is rotatably coupled to the second middle finger link **106***b*, such that middle finger links **106***a*, **106***b*, and **106***c*, form a middle finger able to curl similarly to a human middle finger. A ring finger base **108***d* is rotatably coupled to the palm **102** through a flexure joint **103**. The flexure joint **103** allows the ring finger base **108***d* to rotate around an axis approximately perpendicular to the face of the palm **102**. A first ring finger link **108***a* is rotatably coupled to the ring finger base **108***d* a second ring finger link **108***b*, and a third ring finger link **108***c* such that ring finger links **108***a*, **108***b*, and **108***c*, form a ring finger able to curl similarly to a human ring finger. To the palm **102** is also rotatably coupled a pinky finger base **110***d* through a flexure joint **103** such that the pinky finger base **110***d* can rotate around an axis approximately perpendicular to the palm **102**. To pinky finger base **110***d* is rotatably coupled a first pinky finger link **110***a*, a second pinky finger link **110***b* is rotatably coupled to the first pinky finger link **110***a*, and a third pinky finger link **110***c* is rotatably coupled to the second pinky finger link **110***b*, such that pinky finger links **110***a*, **110***b*, and **110***c*, form a pinky finger able to curl similarly to a human pinky finger. Finger bases **104***d*, **108***d*, and **110***d* are rotatably coupled to palm **102** such that each finger is able to rotate away from the middle finger, allow the fingers to be spread apart similar to the spreading of fingers in a human hand.

A thumb base **112***a* is pivotally coupled to the palm **102** such that the thumb base **112***a* can rotate around an axis approximately parallel to the palm **102**, allowing the thumb base to mimic a flexion movement of a human thumb as an opposable digit to the fingers. A first thumb link **112***b* is rotatably coupled to the thumb base **112***a* such that the first thumb link **112***b* can rotate around an axis approximately perpendicular to the axis of rotation of the thumb base **112***a* allowing the first thumb link to mimic an abduction movement of a human thumb. A second thumb link **112***c* is rotatably coupled to the first thumb link **112***b* and a third thumb link **112***d* is rotatably coupled to the second thumb link **112***c*, such that the second and third thumb links **112***c*, **112***d* can curl towards the face of the palm **102** similarly to the curl of a human thumb.

Index finger base **104***d* is coupled to palm **102** through an index finger linkage comprising a first index linkage link **118***a* and a second index linkage link **118***b* with the index finger base **104***d*, the first index linkage link **118***a*, the second index linkage link **118***b*, and the palm **102** forming a planar one degree-of-freedom four bar index linkage with four links and four flexure joints **103** acting as rotational joints.

Ring finger base **108***d* is coupled to palm **102** through an ring finger linkage comprising a first ring linkage link **116***a* and a second ring linkage link **116***b* with the ring finger base **108***d*, the first ring linkage link **116***a*, the second ring linkage link **116***b*, and the palm **102** forming a planar one degree-of-freedom four bar ring linkage with four links and four flexure joints **103** acting as rotational joints.

Pinky finger base **110***d* is coupled to palm **102** through an pinky finger linkage comprising a first pinky linkage link **114***a* and a second pinky linkage link **114***b* with the pinky finger base **110***d*, the first pinky linkage link **114***a*, the second pinky linkage link **114***b*, and the palm **102** forming a planar one degree-of-freedom four bar pinky linkage with four links and four flexure joints **103** acting as rotational joints.

The second pinky linkage link **114***b* and the second ring finger linkage link **116***b* are further coupled together through a coupling link **120** that transforms the two planar four bar linkages into a planar one degree of freedom eight bar linkage comprising both the four bar pinky linkage and the four bar ring linkage. Further details regarding the operation of these linkages are illustrated in and described with reference to FIG. **3**.

FIG. **2** illustrates a mechanical hand skeleton **200**, according to at least one illustrated implementation. This implementation is similar to the implementation of a mechanical hand skeleton **100** (FIG. **1**), although replaces the flexure joints **103** within the four and eight bar linkages with pin joints **203** (only a subset is indicated to avoid unnecessary cluttering). Other implementations may have a mixture of flexures and linkages, or may employ other types of joints. Structures in FIG. **2** that are identical or similar to corresponding structures in FIG. **1** are identified with the same reference numbers as in FIG. **1**. Only significant differences are discussed below.

The palm **102**, finger bases **104***d*, **106***d*, **108***d*, and **110***d* and the links **114-120** are replaced with a palm **202**, finger bases **204***d*, **206***d*, **208***d*, and **210***d* and links **214-220** respectively which are similar in shape and function but coupled together through pin joints **203** instead flexure joints **103**.

FIG. **3** shows a portion of the mechanical hand skeleton **100** of FIG. **1**, better illustrating various structures thereof. In particular, FIG. **3** better illustrates rotational joints **302***a*-**302***m* that couple together the three finger bases **104***d*, **108***d*, and **110***d* to the linkage links **116***a*, **116***b*, **118***a*, **118***b*, **114***a*, **114***b*, and **120**, and palm **102**. In this implementation the rotation joints **302***a*-**302***m* are flexure joints, but other implementations (e.g., FIG. **2**) may use pin joints or other rotation joints.

These linkages and joints allow for the actuation of a spreading motion of the fingers, similar to the spreading of human fingers. This spreading motion is actuated by coupling a tendon, for example a cable **305**, to a connection point **306** on the second index linkage link **118***b* and threading the cable **305** along a tendon pathway (illustrated by broken line arrow) **304** at least partially delimited by a tube **308** or channel and into the palm **102**. The cable **305** may be tensioned or pulled, and when the cable **305** is pulled, the second ring linkage link **116***b* and the second index linkage link **118***b* are pulled towards each other, rotating about joints **302***k* and **3021** respectively. This causes the index linkage to pull the index base **104***d* down, and the index base **104***d* to rotate around the joint **302***c*. Similarly, the movement of linkage link **116** *b* causes the ring and pinky bases **108***d* and **110***d* to rotate around joints **302***b* and **302***a* respectively in such a way that the four fingers spread apart from one another. A restoring spring or similar bias mechanism (e.g., resilient elastomer) may be placed in a variety of places to restore the linkages to an un-spread or relaxed configuration from a spread or tensioned configuration when the tendon is relaxed, In the illustrated implementation, the restoring spring is placed between the second ring linkage link **116***b* and the second index linkage link **118***b*. Alternatively or additionally, an elastomer (e.g., silicone) skin which envelopes the mechanical hand skeleton **100**, **200** may provide the restoring force and hence constitute a restoring spring member.

The palm **102** and spread mechanism may also have throughholes such as throughholes **310** and throughhole **312**. These throughholes may advantageously provide points of mechanical connection between an elastomer (e.g., silicone) skin and the mechanical hand skeleton **100**, **200** when the elastomer skin is applied to the mechanical hand skeleton **100**, **200**, for example via casting or molding the elastomer skin about or surrounding the mechanical hand skeleton **100**, **200**

FIG. **4** shows the mechanical hand skeleton **100** illustrated with the spread mechanism engaged or tensioned and hence in a relatively spread or tensioned configuration in which at least some of the mechanical digits are spread with respect to one another. Linkage members **102**, **104***d*, **108***d*, **110***d*, **114***a*, **114***b*, **116***a*, **116***b*, **118***a*, and **118***b* and the connected fingers are rotated and positioned as caused by the actuation of the mechanism as described in reference to FIG. **3**.

FIG. **5** shows a back of the mechanical hand skeleton **100**. In particular, a backside of the palm **102** is visible as are tendon cable tubes **502**, **504**, **506**, and **508** which each holds a respective cable, movement of which actuates the curl degree of freedom of a respective one of the four fingers. A backside of each finger and of the thumb includes a series of throughholes **510** (only two called out to prevent clutter) which allow mechanical connection between the mechanical digits and an elastomer (e.g., silicone) skin (see FIG. **7**) which envelopes the mechanical hand skeleton **100**. Similarly, each of the fingers tips includes fingertip throughholes **512** (only one called out to prevent clutter) which allow a mechanical connection between the mechanical digits and an elastomer (e.g., silicone) skin (see FIG. **7**) which envelopes the mechanical hand skeleton **100**.

A wrist connection interface **514** provides a mechanical interface at which the palm **102** connects to a limb or robotic appendage. In at least some implementations, the palm **102** may be pivotally or rotatably connected to a limb or robotic appendage. In at least some implementations, the palm **102** may be removable pivotally or rotatably connected to a limb or robotic appendage, for example via a quick-release coupler (e.g., bayonet mount).

FIG. **6** better illustrates aspects of the wrist connection interface **514** of the palm of the mechanical hand skeleton **100**, **200**. Wrist connection interface **514** includes a mechanical connection cutout **601** for connection with a wrist or other limb structure. The mechanical connection cutout **601** may also provide a conduit or passage to route sensor or electrical signal wiring or optical fiber therethrough. The wiring or optical fiber may communicatively couple one or more sensors (e.g., tactile sensors, pressure sensors, inductive sensors, capacitive sensors, thermal sensors, force sensors) on the mechanical hand to one or more processors or controllers that are part of a robot. Tendon cable connection ports **602**-**616** are entry points for cables that connect to the various actuation degrees of freedom of the hand, including the curl of the four fingers, the curl, flexion, and abduction degrees of freedom of the thumb, and the finger spread mechanism. The cables may be attached to actuators (e.g., electric motors, solenoids, pneumatic or hydraulic pistons) that are part of a robot.

FIG. **7** shows a mechanical hand **700** comprising a mechanical hand skeleton **100** after casting in an elastomer (e.g., silicone). The mechanical hand skeleton **100** is fully enveloped and imbedded in a soft elastomer skin **702** that is cast with the mechanical hand skeleton **100** in place. The elastomer skin is preferably silicone. The method for creating this skinned mechanical hand **700** includes suspending a mechanical hand skeleton **100**, **200** with required tendons, sensors, and electronics attached in a mold, the mold having an internal cavity with a shape that resembles a human hand. The elastomer (e.g., a liquid silicone mixture) is then introduced (e.g., poured, pumped) into the internal cavity of the mold, cover the exterior surfaces of the mechanical hand skeleton **100**, **200** as well as entering into various cavities and openings between components of the mechanical hand skeleton **100**, **200**. The elastomer is then cured (e.g., catalyzed, heated, exposed to ultraviolet light, etc.) to form the elastomer skin.

FIG. **8** shows a mechanical hand **801** that includes a mechanical hand skeleton **800** and electrical and/or electronic components (i.e., circuitry). This implementation of the mechanical hand skeleton **800** omits a spread mechanism, but otherwise has a largely similar mechanical structure to other ones of the described implementations. For example, the mechanical hand skeleton **800** includes a palm **802**, a thumb **804**, an index finger **806**, a middle finger **808**, a ring finger **810**, and a pinky finger **812**. Notably, each of the index, middle, and ring fingers **806**, **808**, **810** have a respective ribbon cable box **816** coupled to their base. The ribbon cable boxes **816** hold excess lengths of electrical ribbon cables **818** which are communicatively coupled to sensors carried by the index, middle, and ring fingers **806**, **808**, **810**. The ribbon cables **818** may naturally retract back into the ribbon cable boxes **816** due to bending stresses in the ribbon cables **818** when the finger is relaxed or may have a spring or other bias mechanism, for instance where the ribbon cables **818** are resilient. Other implementations may have similar ribbon cable boxes on the pinky finger base or thumb base, or may have ribbon cable box on some other combination of fingers. Coupled to the back of the palm **802** is a first printed circuit board **814**. The first printed circuit board **814** may carry sensors (e.g., pressure sensors, temperature sensors, force sensors, inductive or capacitive touch sensors), for instance to detect interactions of the palm with various objects, and/or electronic processors or controllers operable to collect and processor sensor data from sensors carried by the fingers, thumb, and other printed circuit boards. The first printed circuit board **814** may carry one or more communications ports wired operable to and transmit raw or processed senor data to other systems (e.g., a robot control system). The communications ports may take the form of wired (e.g., electrical, optical) and/or wireless (e.g., radio and antenna) communications ports.

FIG. **9** shows the mechanical hand **801** from the obverse side to that of FIG. **8**. As visible in FIG. **9**, the mechanical hand **801** includes a second printed circuit board **820**. The second printed circuit board **820** may hold sensors (e.g., pressure sensors, temperature sensors, force sensors, inductive or capacitive touch sensors) and electronic processors operable to collect and/or process sensor data from sensors carried by the fingers, thumb, and boards. The second printed circuit board **820** may carry one or more communications ports operable to transmit raw or processed sensor data to other systems (e.g., a robot control system). The communications ports may take the form of wired (e.g., electrical, optical) and/or wireless (e.g., radio and antenna) communications ports. The second printed circuit board **820** may be communicatively coupled to the first printed circuit board **816** to allow for centralized processing or transmitting of sensor data.

FIG. **10** depicts a cross-sectional view of an example implementation of a mechanical finger **1000** that may be used as any of the index, middle, ring, or pinky fingers as previously illustrated and described. The illustrated mechanical finger **1000** comprises a finger base **1002**, first finger link **1004**, second finger link **1006**, finger curl link **1008** and fingertip **1010**. The finger base **1002** supports the mechanical finger **1000** from the palm (not illustrated in FIG. **10**). Alternatively, in some implementations, the finger base **1002** may be part of the palm. The first finger link **1004** is coupled to the finger base **1002**, the second finger link **1006** is coupled to the first finger link **1004** and the finger curl link **1008** is coupled to the second finger link **1006**. Both the second finger link **1006** and the finger curl link **1008** are coupled to the fingertip **1010**. The first finger link **1004** is pinned to the finger base **1002** at pin joint **1007***a* to allow pivoting or rotation thereabout. The second finger link **1006** is pinned to the first finger link at pin joint **1007***b* to allow pivoting or rotation thereabout. The fingertip **1010** is pinned to the second finger link **1006** at pin joint **1007***d*. The finger curl link **1008** is pinned to the first finger link at pin joint **1007***c* and is pinned to the fingertip **1010** at pin joint **1007***e*.

A sensor (e.g., pressure sensor, temperature sensor, force sensor, inductive or capacitive touch sensor) **1012** is coupled to the fingertip **1010**. The sensor **1012** is coupled to a ribbon cable **1013** which carries power and electrical signals and information both to and from the sensor **1012**. The ribbon cable **1013** may begin at the base of the finger at **1014** passes through a cavity **1018** and exits the cavity **1018** towards the remainder of the mechanical finger **1000**. The ribbon cable **1013** has some extra length **1016** (e.g., folded) held by the cavity **1018**. The ribbon cable **1013** extends from the cavity **1018** to the second finger link **1006**, and threads between the second finger link **1006** and the finger curl link **1008**. The ribbon cable **1013** extends out to the front of the fingertip **1010** where the ribbon cable **1013** communicatively couples to the sensor **1012**. The extra length **1016** in the ribbon cable **1013** ensures that there is sufficient extra length to extend the ribbon cable **1013** with the finger links when the finger links curl.

The curling of the mechanical finger **1000** is actuated via a cable. The cable may be threaded through a path in the finger base **1022**, around a cylindrical surface, along a path through the first finger link **1024**, and around a cylindrical surface on the second finger link, and attached to an attachment point **1025** on the second finger link **1006**. Tensioning of the cable shortens a path the cable takes through the mechanical finger **100**, causing the first finger link **1004** to rotate clockwise around the pin joint **1007***a* to shorten the path around the cylindrical surface. Tensioning of the cable also causes the second finger link **1006** to rotate clockwise around pin joint **1007***b*. The rotation of the second finger link actuates the four-bar linkage formed by links **1004**, **1006**, **1008**, and **1010**, causing that the fingertip **1010** to rotate clockwise. A spring or other bias member can be coupled between connection points **1026** and **1028** on the finger base **1002** and second finger link **1006** respectively, to apply a restorative force to return the finger to the neutral or relaxed position when tension is removed from the cable.

FIG. **11** shows a portion of a mechanical hand skeleton **1100** with three ribbon cable boxes **816**, three electrical ribbon cables **1102**, **1104**, **1106**, and the first printed circuit board **814**. The illustrated implementation comprises three ribbon cables **1102**, **1104**, and **1106** which communicatively couple three fingers sensors (not visible in FIG. **11**) with a controller or processor **1112** (e.g., micro-controller, microprocessor, application specific integrated circuit, digital signal processor, graphic processing unit, field programmable gate array, programmed logic controller) carried by the first printed circuit board **814**. In some implementations, the first printed circuit board **814** may also carry or bear one or more sensors (e.g., pressure sensors, temperature sensors, force sensors, inductive or capacitive touch sensors) **1108** and **1110** communicatively coupled with the controller or processor **1112**. The processor **1112** may be communicatively coupled to one or more external systems, for example via a communications cable **1114**. The processor **1112** may also be communicatively coupled to other sensors, for example sensors positioned on the palm, thumb, fingers, or carried by other printed circuit boards.

FIG. **12** shows a portion of a mechanical hand skeleton **1200** with the second printed circuit board **820**. The illustrated implementation comprises a number of sensors **1202** (e.g., pressure sensor, force sensor, inductive or capacitive touch sensors) coupled to a controller or processor **1204** (e.g., micro-controller, microprocessor, application specific integrated circuit, digital signal processor, graphic processing unit, field programmable gate array, programmed logic controller) carried by the second printed circuit board **820**. The processor **1204** may be communicatively coupled to one or more external systems or to other circuit boards attached to the mechanical hand skeleton **1200**. The processor **1204** may also be communicatively coupled to other sensors carried by the palm, thumb, fingers, or other printed circuit boards such as first printed circuit board **814**.

The various implementations and embodiments described above can be combined to provide further implementations and embodiments. Various changes can be made to the implementations and embodiments in light of the above-detailed description. For example, the described methods may include additional acts, omit some acts, and/or perform acts in a different order. Various methods or operations may be performed across multiple processors, which may be in a distributed environment. Various changes can be made to the implementations and embodiments in light of the above-detailed description. To the extent that they are not inconsistent with the specific teachings and definitions herein, all of the U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet, including but not limited to U.S. Provisional Application No. 62/937,044, filed Nov. 18, 2019, are incorporated herein by reference, in their entirety. Aspects of the embodiments can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments.

In general, in the following claims, the terms used should not be construed to limit the claims to the specific implementations and embodiments disclosed in the specification and the claims, but should be construed to include all possible implementations and embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

The terms "approximately equal", "approximately parallel", approximately perpendicular" as may be used in the description and claims to compare or relate two or more entities, encompass variations to the described entities that are similar enough to have the same or similar functionality.

The invention claimed is:

1. A mechanical hand comprising:

a hand skeleton comprising:

a palm; and

a plurality of mechanical digits, each of the mechanical digits having a base coupled to the palm and comprising at least three mechanical links and at least two curl joints, each pair of successive mechanical links along each of the mechanical digits pivotally coupled to one another via a respective one of the at least two curl joints;

a first sensor coupled to a first mechanical digit from the plurality of mechanical digits; and a skin of elastic material completely enveloping the hand skeleton.

2. The mechanical hand of claim **1**, wherein the skin of elastic material is mechanically coupled to the hand skeleton.

3. The mechanical hand of claim **1**, wherein the first sensor is coupled to the mechanical link at a tip of the first mechanical digit.

4. The mechanical hand of claim **3**, wherein the first sensor is at least one of a pressure sensor or a touch sensor.

5. The mechanical hand of claim **3**, wherein the skin of elastic material envelopes the first sensor.

6. The mechanical hand of claim **3**, further comprising a first wire electrically coupled to the first sensor, wherein the first wire extends through a cavity formed in at least one of the mechanical links of the first mechanical digit.

7. The mechanical hand of claim **6**, wherein the first wire has an excess length permitting curling of the first mechanical digit.

8. The mechanical hand of claim **1**, wherein the base of the first mechanical digit is rotatably coupled to the palm through a flexure joint.

9. The mechanical hand of claim **8**, wherein the first mechanical digit is coupled to the palm through a first linkage.

10. The mechanical hand of claim **9**, further comprising a first tendon coupled to the first linkage and extending through a tube disposed on the palm.

11. The mechanical hand of claim **10**, wherein the skin of elastic material envelopes the first tendon, the first linkage, and the tube.

12. The mechanical hand of claim **1**, wherein the skin of elastic material is molded onto the hand skeleton.

13. The mechanical hand of claim **1**, further comprising at least one printed board circuit coupled to the palm, wherein the at least one printed board circuit carries a plurality of sensors.

14. The mechanical hand of claim **1**, further comprising a plurality of sensors coupled to the plurality of mechanical digits.

15. The mechanical hand of claim **14**, wherein the skin of elastic material envelopes the plurality of sensors.

16. The mechanical hand of claim **1**, further comprising a mechanical wrist connection interface coupled to the palm and covered at least partially by the skin of elastic material.

17. A method comprising:

forming a hand skeleton comprising a palm and a plurality of mechanical digits coupled to the palm, each of the mechanical digits having a base coupled to the palm and comprising at least three mechanical links and at least two curl joints, each pair of successive mechanical links along each of the mechanical digits pivotally coupled to one another via a respective one of the at least two curl joints;

coupling a plurality of sensors to the plurality of mechanical digits; and

molding a skin of elastic material over the hand skeleton to completely envelope the hand skeleton.

18. The method of claim **17**, wherein coupling the plurality of sensors to the plurality of mechanical digits comprises coupling each of the sensors to the mechanical digit at a tip of one of the mechanical digits, and wherein molding the skin of elastic material over the hand skeleton to completely envelope the hand skeleton comprises molding the skin of elastic material over the hand skeleton to complete envelope the plurality of sensors.

19. The method of claim **18**, wherein molding the skin of elastic material over the hand skeleton to completely envelope the hand skeleton comprises extending portions of the skin of elastic material through a plurality of holes formed in at least one of the palm or mechanical digits to mechanically couple the skin of elastic material to the hand skeleton.

20. The method of claim **17**, further comprising:

extending a plurality of tendons through a plurality of tubes coupled to the palm; and

coupling each of the plurality of tendons to at least one of the mechanical links of at least one of the mechanical digits;

wherein molding the skin of elastic material over the hand skeleton to completely envelope the hand skeleton comprises molding the skin of elastic material to completely envelope the plurality of tendons and the plurality of tubes.

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